

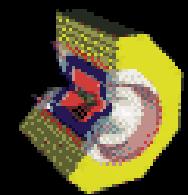
May 18-21, 2010 Fermilab

# Radiative Decays of Charmonia at CLEO

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on behalf of the CLEO Collaboration



# Outline

**Radiative charmonium decays provide opportunities for various measurements:**

- **Exclusive branching fractions**

- $J/\psi, \psi(2S), \psi(3770) \rightarrow \gamma + \pi^0 / \eta / \eta'$  PRD 79, 111101(R) (2009)

- **Parton-level branching fractions**

- $\psi(2S) \rightarrow \gamma g g$  PRD 80, 072002 (2009)

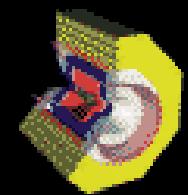
- **BSM searches**

- $J/\psi \rightarrow \gamma + \text{invis}$  arXiv: 1003.0417[hep-ex]  
Accepted by PRD

Not covered today

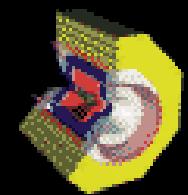
Previously from CLEO:

- $J/\psi \rightarrow \gamma g g$
- $J/\psi \rightarrow \gamma \gamma \gamma$
- $\chi_{cJ} \rightarrow \gamma \gamma$
- $\chi_{cJ} \rightarrow \gamma \rho / \omega / \phi$
- $\eta'$  mass from  $J/\psi \rightarrow \gamma \eta'$



# CLEO-c Datasets

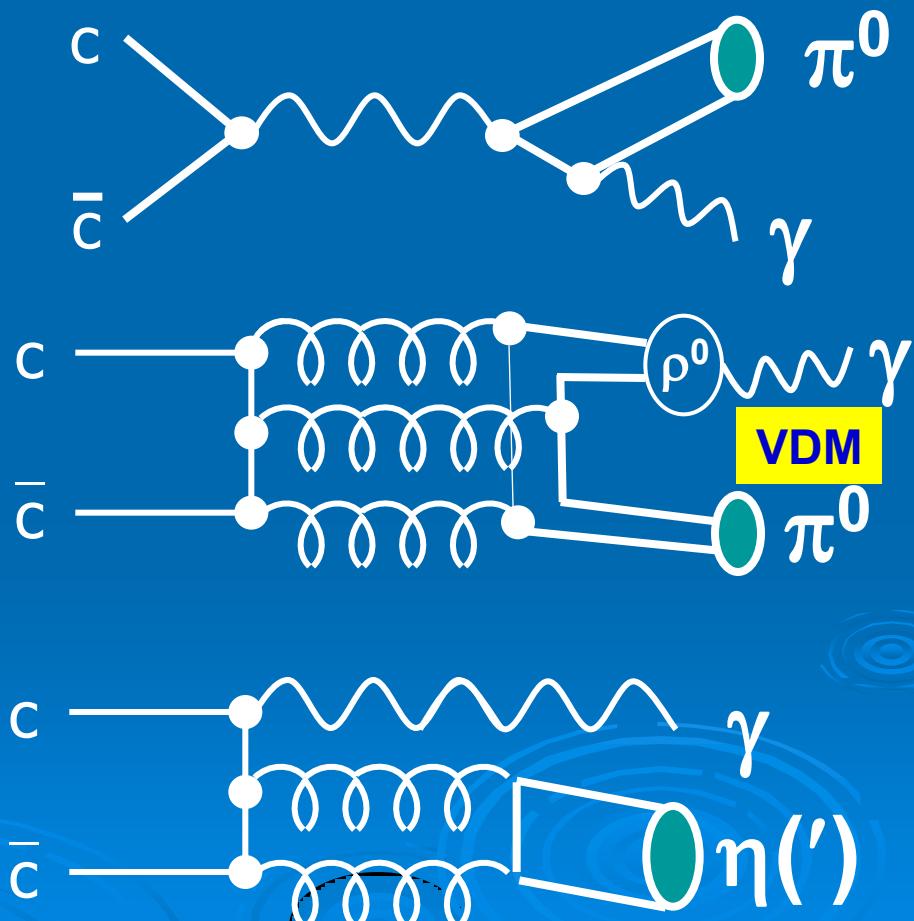
- $\psi(2S)$  :  $27.36 \pm 0.57$  M ( 54/pb)
- $\sqrt{s}=3671$  : ( 21/pb)
- $\pi^+\pi^- J/\psi$  :  $9.59 \pm 0.07$  M
- $\psi(3770)$  :  $5.3 \pm 0.1$  M (814/pb)
- Continuum data sample only 1/37<sup>th</sup> of  $\psi(3770)$  luminosity: not very useful for that dataset
- Continuum scaled up by factor of 2.6 for  $\psi(2S)$

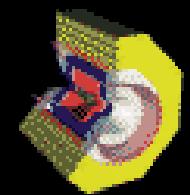


# BRs for $J/\psi$ , $\psi(2S)$ , $\psi(3770) \rightarrow \gamma + \pi^0 / \eta / \eta'$

- $c\bar{c} \rightarrow \gamma \pi^0$ 
  - Not  $\gamma gg$  (isospin)
  - Comparable e-m & VDM
  - Predicted  $B \approx 4 \times 10^{-5}$
  - Measured  $B = 3.3^{+0.6}_{-0.4} \times 10^{-5}$
- $c\bar{c} \rightarrow \gamma \eta(')$ 
  - $\gamma gg$  dominant
- $\gamma \eta' / \gamma \eta = 4.8$  from  $J/\psi$ 
  - expect a similar value at  $\psi(2S)$  due to flavor blindness of  $gg$
  - $\psi(2S) : > 1.5$  in PDG08
- $\psi(3770)$ 
  - Non- $D\bar{D}$  decays?

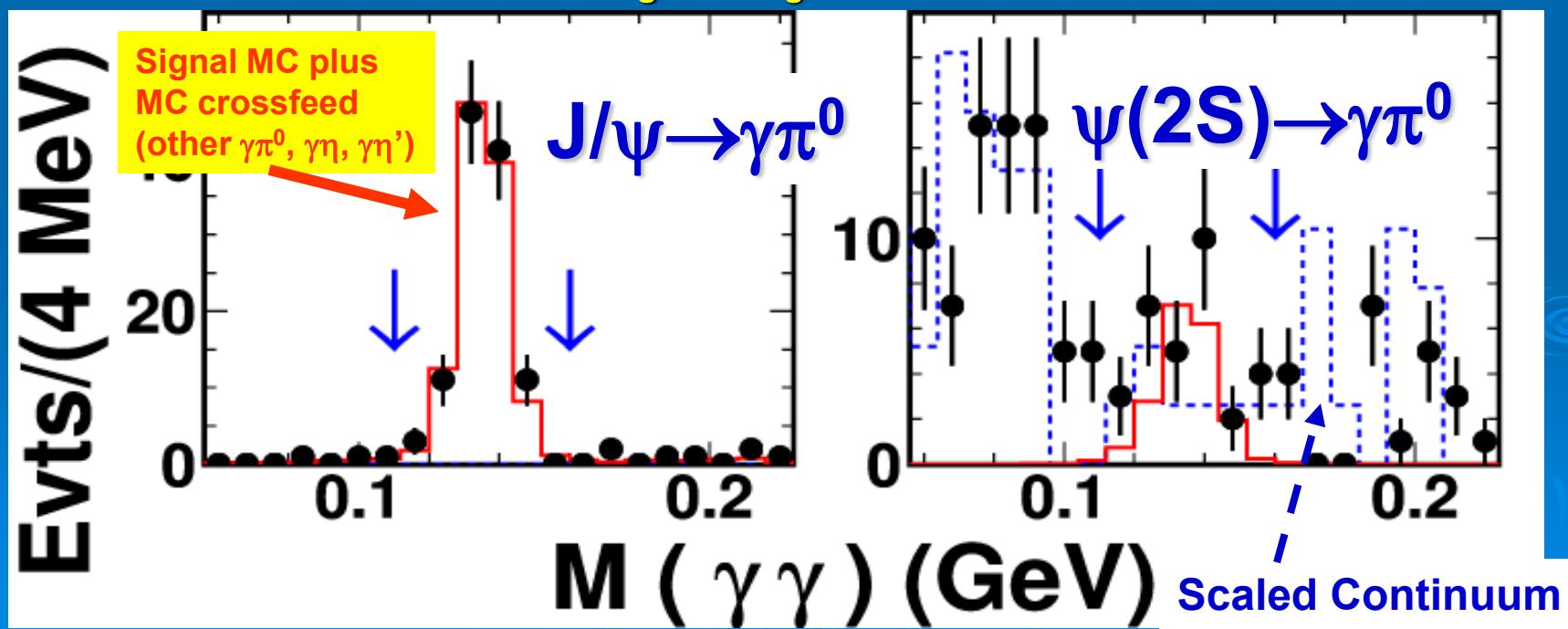
Chernyak & Zhitnitsky  
Phys Rep 112, 173 (1984)

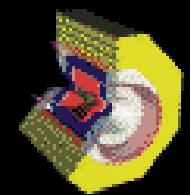




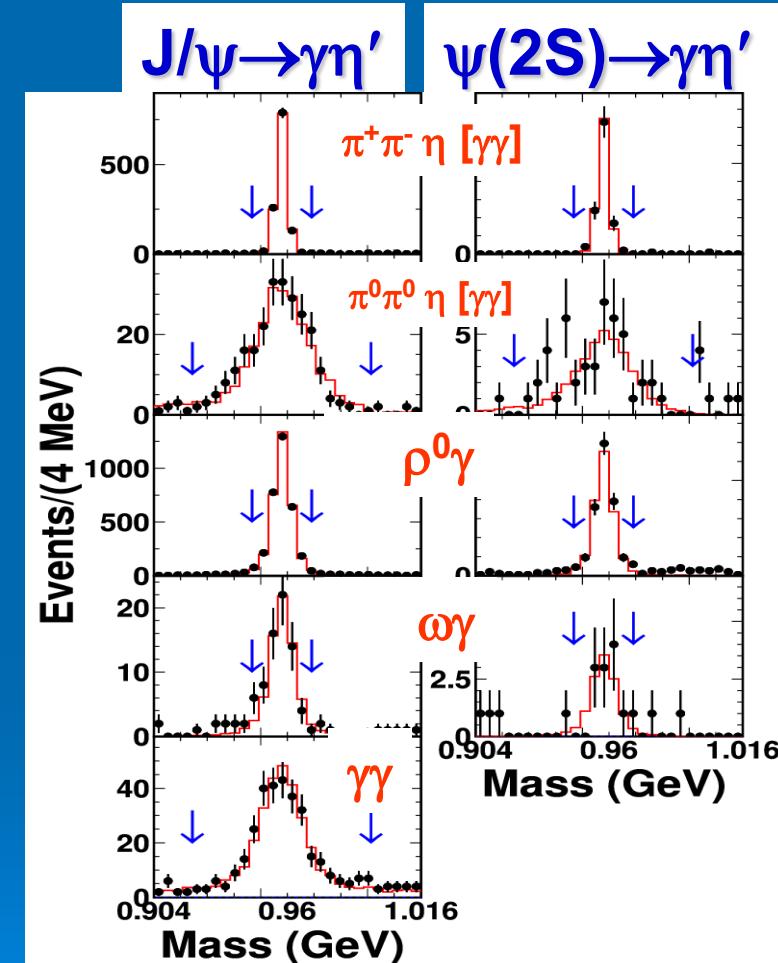
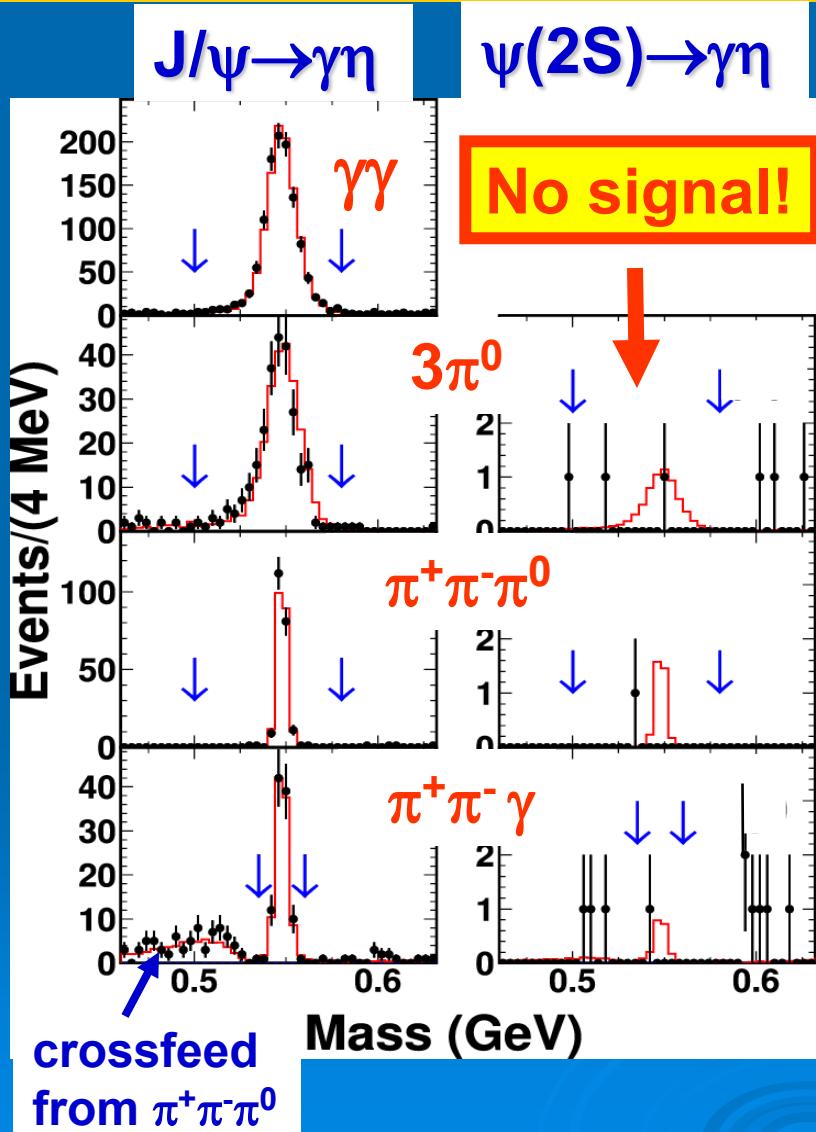
# BRs for $\gamma + \pi^0 / \eta / \eta'$

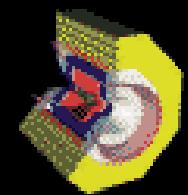
- Full reconstruction + kinematic fit
- Use  $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$  for  $J/\psi$
- Decay products are highly collimated due to the low masses of  $\pi^0$ ,  $\eta$ ,  $\eta'$  & high boost
  - Photon shower selection allows for crowded environment to maintain high efficiency
- Cut 'n count
  - Use MC for efficiencies & feed-across
  - Continuum data for  $e^+ e^-$  bgd for  $\psi(2S)$  data
  - Use mass sidebands for remaining small bgds





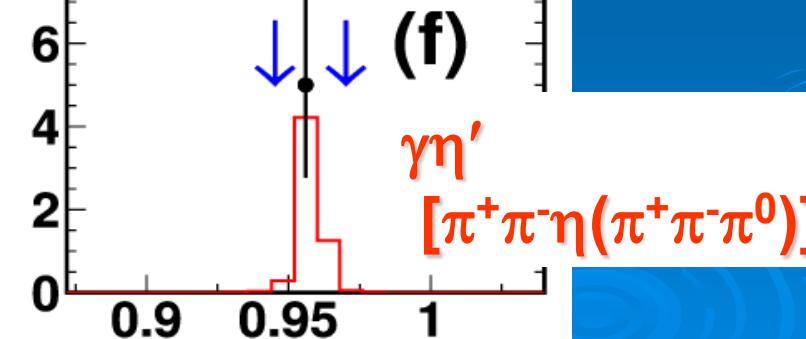
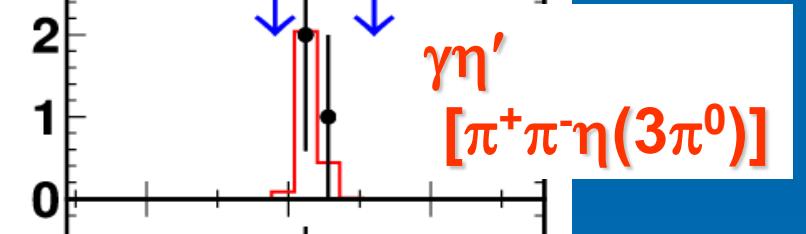
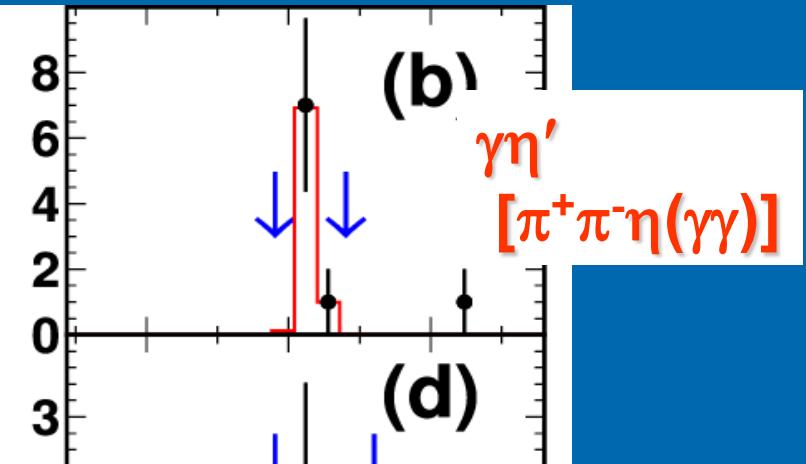
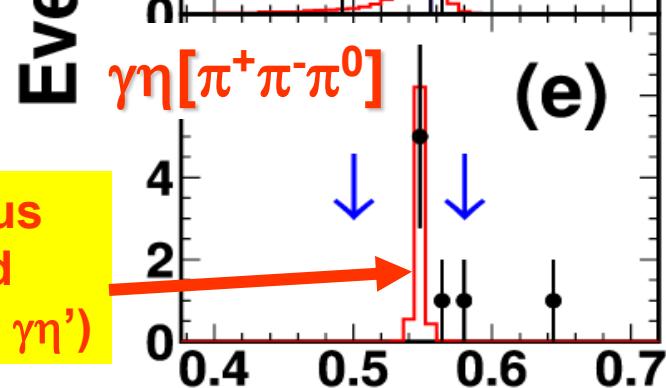
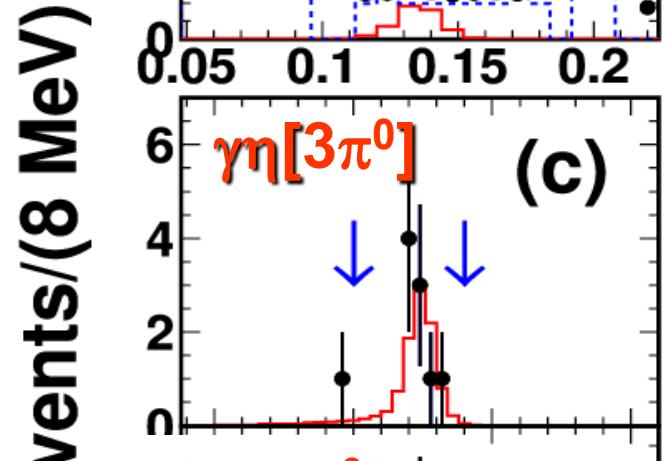
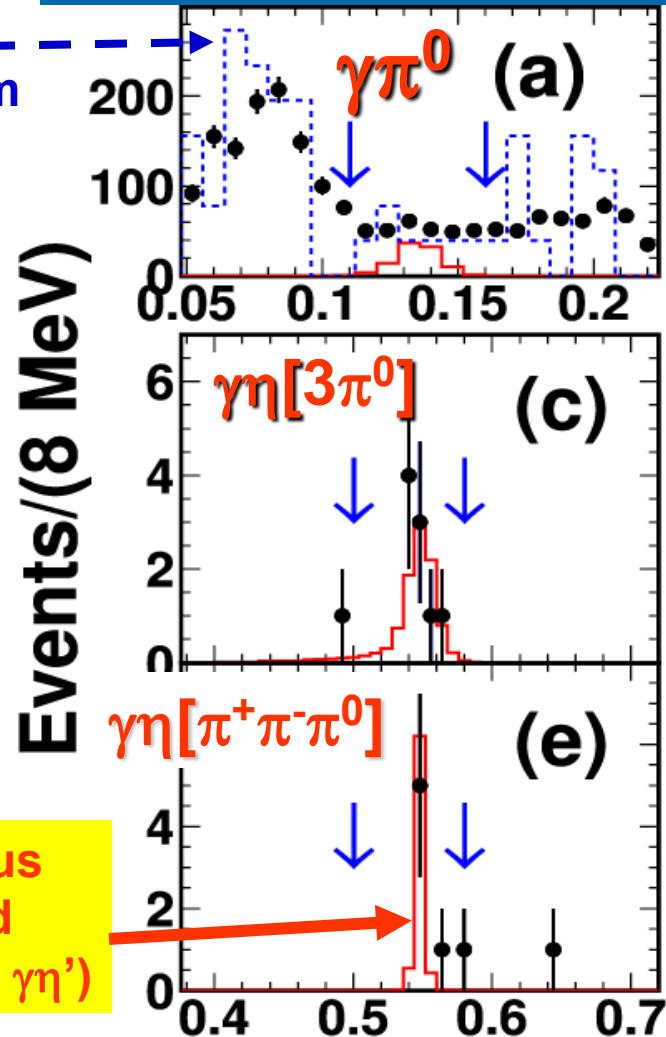
# $J/\psi, \psi(2S) \rightarrow \gamma\eta, \gamma\eta'$



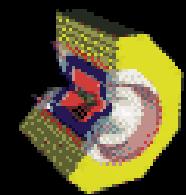


# $\psi(3770)$ : Signals?

Scaled  
Continuum



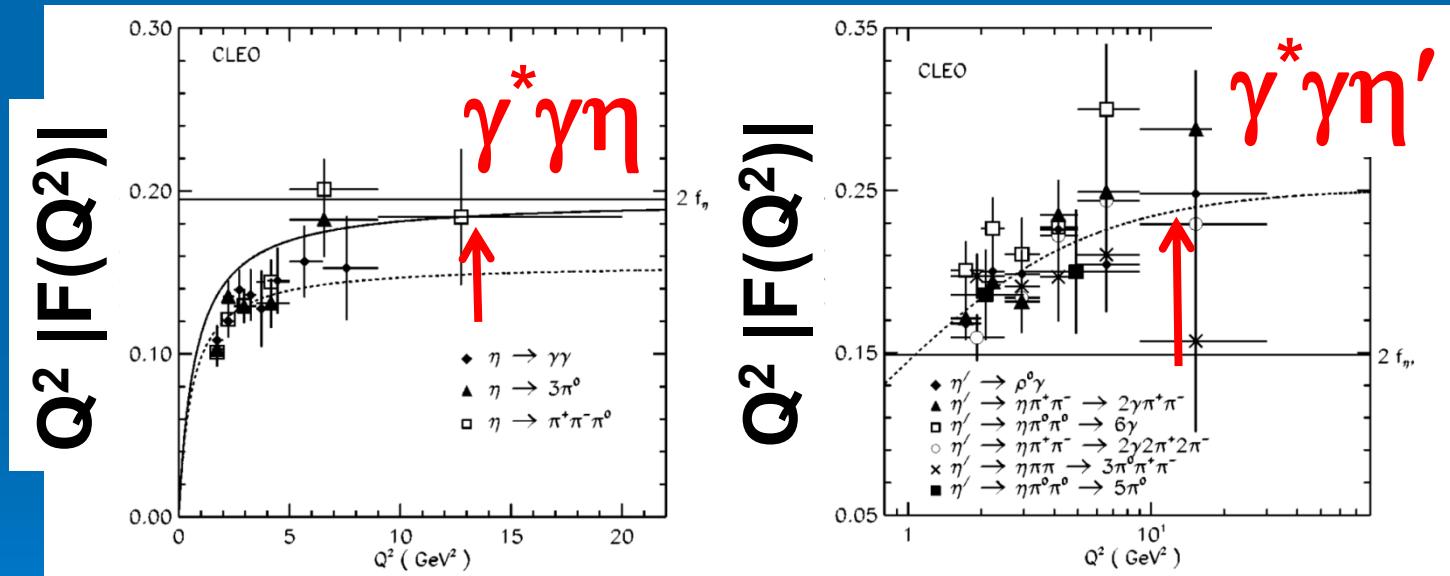
Signal MC plus  
MC crossfeed  
(other  $\gamma\pi^0$ ,  $\gamma\eta$ ,  $\eta\eta'$ )



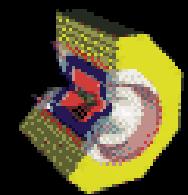
# Continuum Backgrounds

Can extrapolate from BaBar [ PRD74, 012002 (2006) ]

- $\sigma(e^+e^- \rightarrow \gamma\eta) = 4.5^{+1.2}_{-1.1} \pm 0.3 \text{ fb at } \sqrt{s} = 10.58 \text{ GeV}$
- $\sigma(e^+e^- \rightarrow \gamma\eta') = 5.4 \pm 0.8 \pm 0.3 \text{ fb at } \sqrt{s} = 10.58 \text{ GeV}$
- Use CLEO form factor measurements [ PRD57, 3 (1998) ]



- Scale BaBar  $\sigma$ 's as  $|F(Q^2)|^2 \sim 1/s^4$  : factor of ~50-60
- $\psi(2S)$ : ~1 event each;  $\psi(3770)$ : 10-20 events each

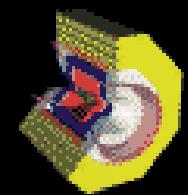


# $\gamma + \pi^0 / \eta / \eta'$ Results

- Improve precision everywhere!
  - $J/\psi \rightarrow \gamma\eta$  rate confirms BES values (earlier, smaller values suspect)
- Consistent with previous less precise results
- Signal for  $\psi(3770) \rightarrow \gamma\eta$  &  $\gamma\eta'$ ? (16 events each!)
  - But expect ~ this number from continuum!
- $B(\gamma\eta') / B(\gamma\eta) > 59$  from  $\psi(2S)$ . Is ~5 on  $J/\psi$ . Why??

Mode	This result ( $10^{-4}$ )	PDG ( $10^{-4}$ )	$\sigma$
$J/\psi \rightarrow \gamma\pi^0$	$0.363 \pm 0.036 \pm 0.013$	$0.33^{+0.06}_{-0.04}$	0.4
$\rightarrow \gamma\eta$	$11.01 \pm 0.29 \pm 0.22$	$9.8 \pm 1.0$	1.2
$\rightarrow \gamma\eta'$	$52.4 \pm 1.2 \pm 1.1$	$47.1 \pm 2.7$	1.7
$\psi(2S) \rightarrow \gamma\pi^0$	$<0.05$	$<54$	...
$\rightarrow \gamma\eta$	$<0.02$	$<0.9$	...
$\rightarrow \gamma\eta'$	$1.19 \pm 0.08 \pm 0.03$	$1.36 \pm 0.24$	-0.7
$\psi(3770) \rightarrow \gamma\pi^0$	$<2$	...	...
$\rightarrow \gamma\eta$	$<0.2(1.5)$		
$\rightarrow \gamma\eta'$	$<0.2(1.8)$		

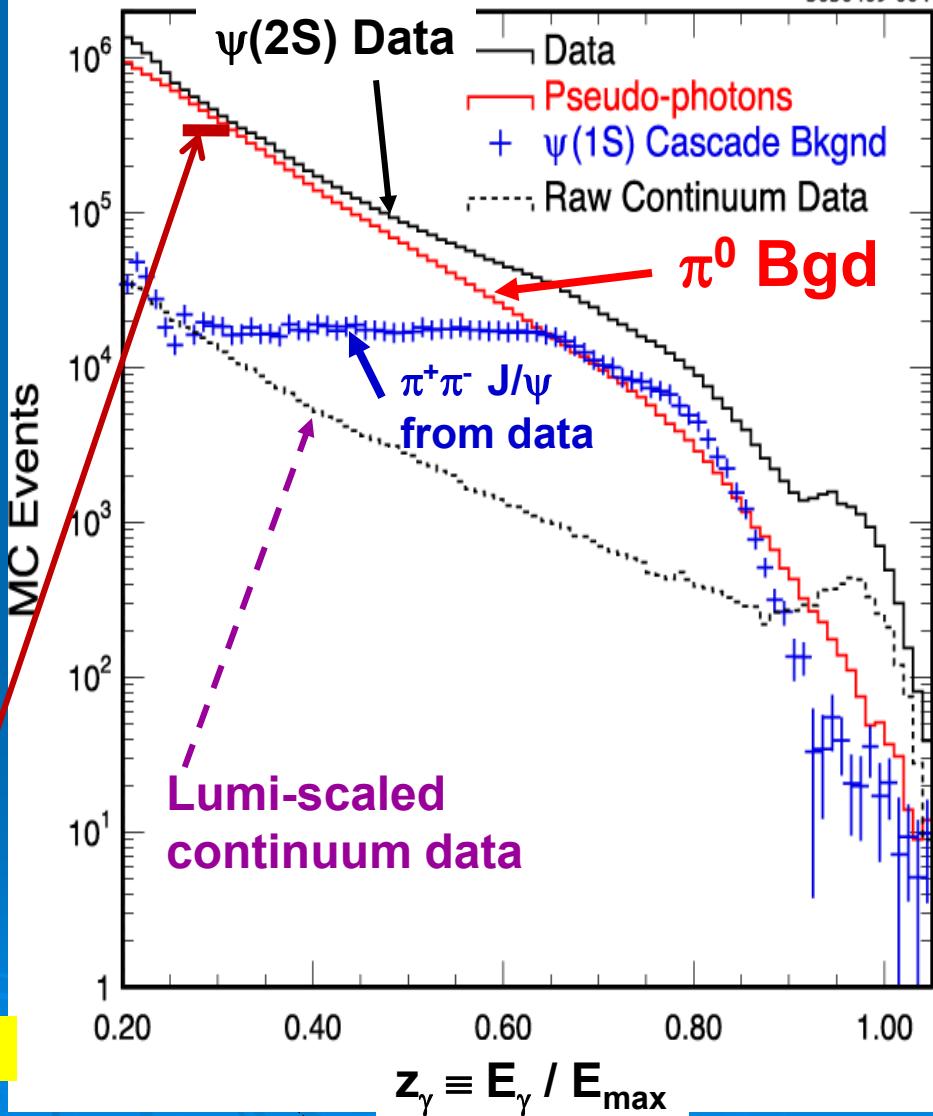
Assuming no (maximal destructive) interference

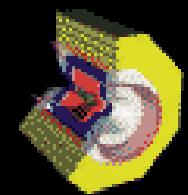


# $\psi(2S) \rightarrow \gamma gg$

3030409-004

- Define  $z_\gamma \equiv E_\gamma / E_{\max}$
- Challenge is isolating parton-level photon with big subtractions
- Continuum: ISR effects
- Transitions:
  - Use shape from dipion tags:  $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$
  - Correct for  $\epsilon$ ,  $B(\text{any } J/\psi) / B_+$ .
  - $\psi(2S) \rightarrow \gamma \chi_{cJ}$  from MC
- Biggest:  $\pi^0$ 's. Use 2 data-driven methods)
  - “Pseudo-photons”
    - Use measured  $\pi^\pm$  spectrum + isospin symmetry to generate
  - Exponential
    - Fit subtracted data in  $z_\gamma = 0.27 - 0.32$
    - Extrapolate to all  $z_\gamma$





# Results for $\psi(2S) \rightarrow \gamma gg$



3030409-005

- Integrate data for  $z_\gamma > 0.4$

- Correct for  $\epsilon$  (see inset)
- Correct for  $z_\gamma < 0.4 / z_\gamma > 0.4$   
➢ ~28% of  $\gamma$ 's have  $z_\gamma < 0.4$
- # $\psi(2S)$  = 27M
- $B(\gamma gg) \approx 1.02 \pm 0.29\%$

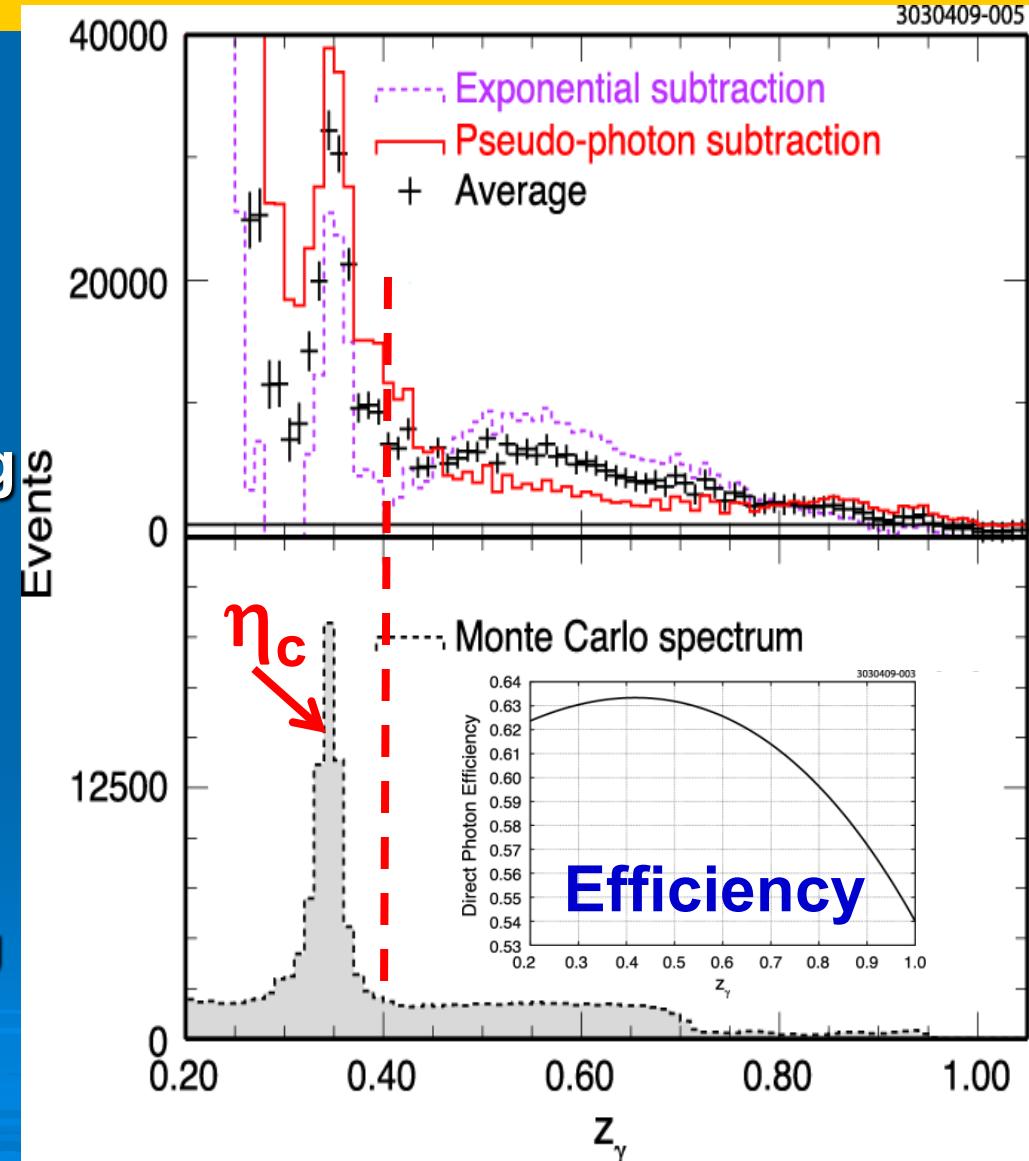
- But we want ratio to ggg

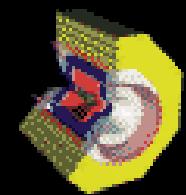
- $\Sigma B[\psi(2S) \rightarrow$

- $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$  (PDG)
- $\gamma^* \rightarrow qq$  (PDG)
- $\pi\pi J/\psi$ ,  $\eta/\pi^0 J/\psi$  (CLEO)
- $\gamma \chi_{cJ}$ ,  $\gamma \eta_c$ ,  $\pi^0 h_c$

≈ 88%.

- Leaves ~12% for  $\gamma gg + 3g$
- $B(ggg) \approx 10.6 \pm 1.6\%$





# Results for $\psi(2S) \rightarrow \gamma gg$ (2)

- Statistical errors are negligible
- Systematics

- 27% for background subtraction
- 15% for  $\psi(2S)$  branching fractions
- 7% for  $z\gamma < 0.4$  extrapolation
- 32% total systematic error
- (room for improvement!)

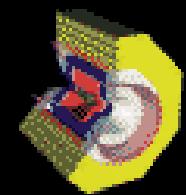
$$R_\gamma \equiv B(\gamma gg)/B(ggg) = 0.097 \pm 0.031$$

(0.137  $\pm$  0.017 for  $J/\psi$ )

Difference is  $\sim 1.1\sigma$

Reminder: for  $\Upsilon(1S,2S,3S) \rightarrow \gamma gg$ ,  
CLEO measurements yielded  
 $R_\gamma \approx 0.03$  within  $\sim 10\text{-}15\%$  errors

[ PRD74 (2006) 012003 ]



# J/ψ → γ + invisible

- Some non-minimal SUSY models allow CP-odd Higgs  $A_s \rightarrow \tilde{\chi}\tilde{\chi}$  (DM candidate)

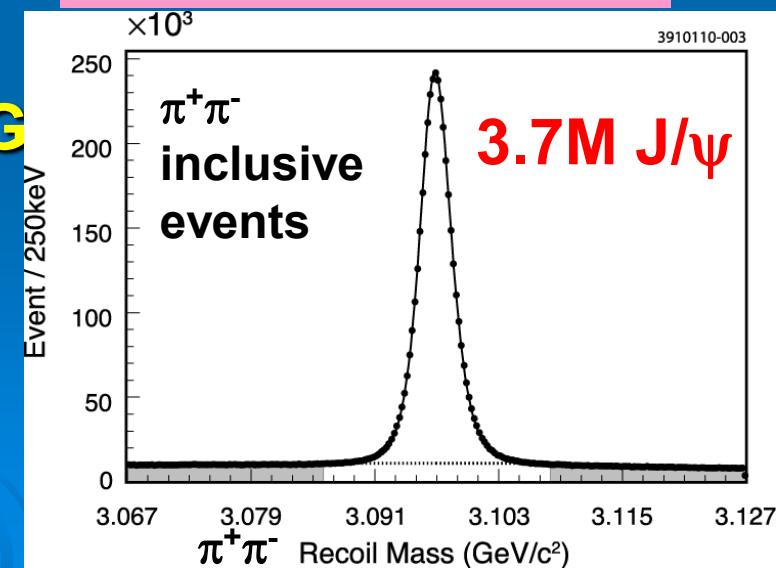
- $a_1 = A_{\text{MSSM}} \cos\theta + A_s \sin\theta$

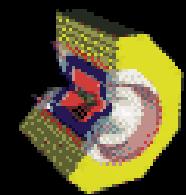
- Look for  $J/\psi \rightarrow \gamma + \text{invis}$  in  $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$

$$\frac{\Gamma(J/\psi \rightarrow \gamma X)}{\Gamma(J/\psi \rightarrow \mu^+ \mu^-)} \approx \frac{G_F m_c^2}{2\sqrt{2} \alpha \pi} \frac{\cos^2 \theta}{\tan^2 \beta}$$

- Select  $\pi^+ \pi^-$  plus  $\gamma$  + **NOTHING**
- $E_\gamma^* > 1.25 \text{ GeV}$
- Good shower shape**
  - Cuts  $\pi^+ \pi^-$ -induced “satellite” or “splitoff” showers plus anti-neutrons

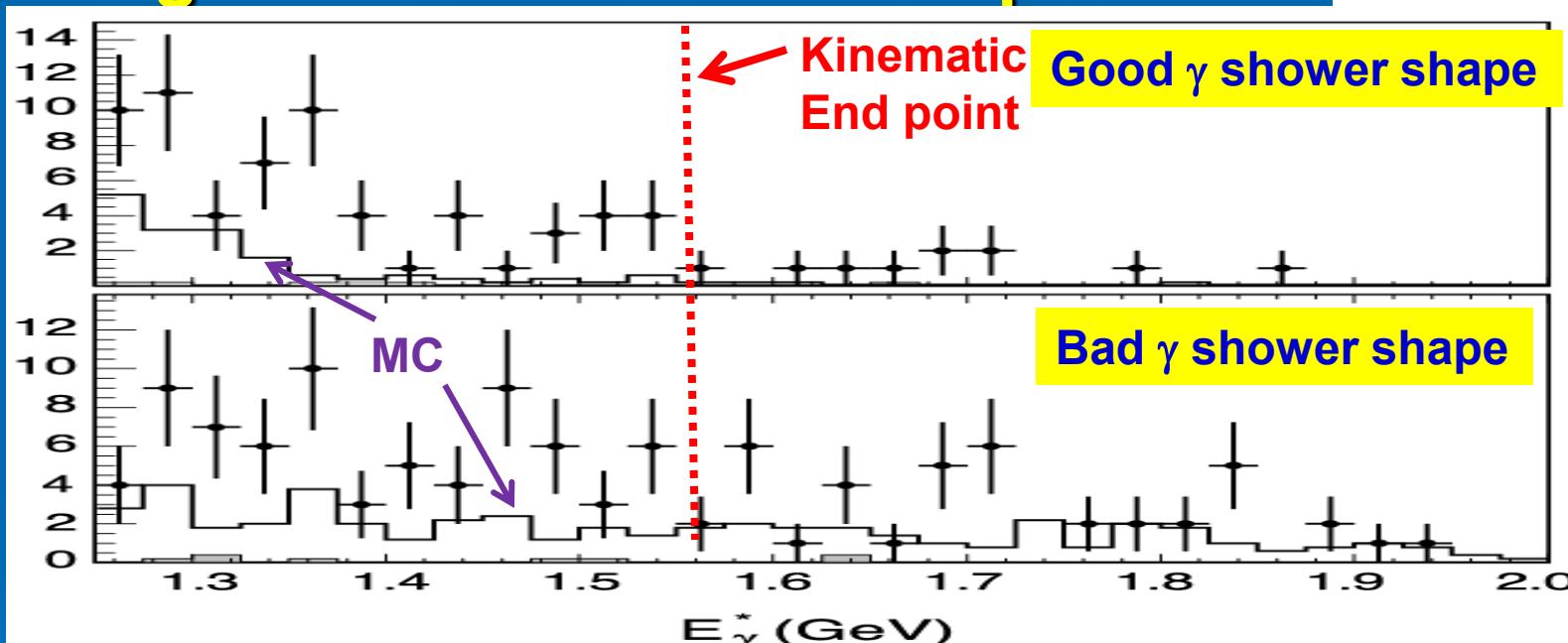
For  $\Upsilon(nS) \rightarrow \gamma a_0$ , the  $\tan^2 \beta$  term is in the numerator





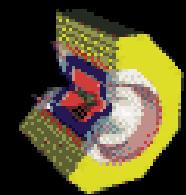
# Bgd for $J/\psi \rightarrow \gamma + \text{invis}$

- Plot  $E_\gamma^*$  spectrum: in  $J/\psi$  rest frame
  - Signal would be a narrow peak



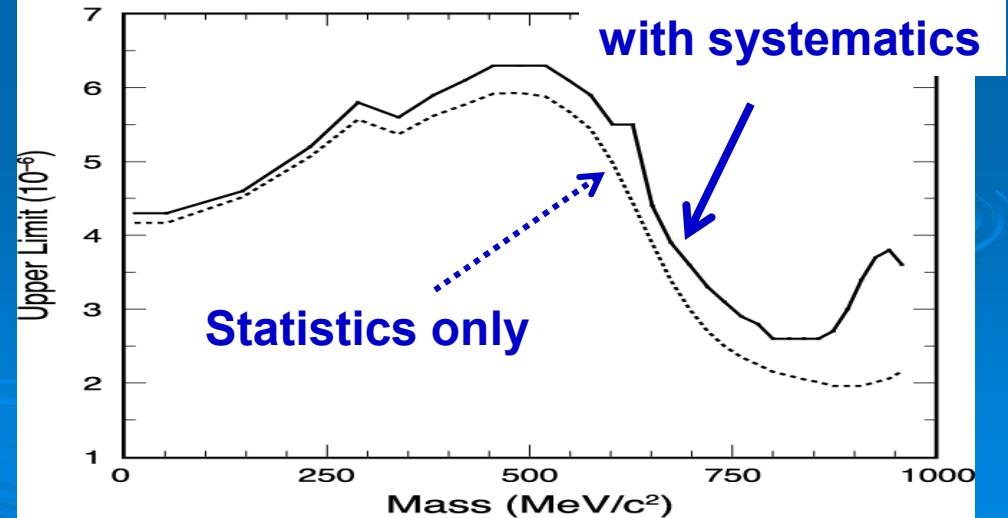
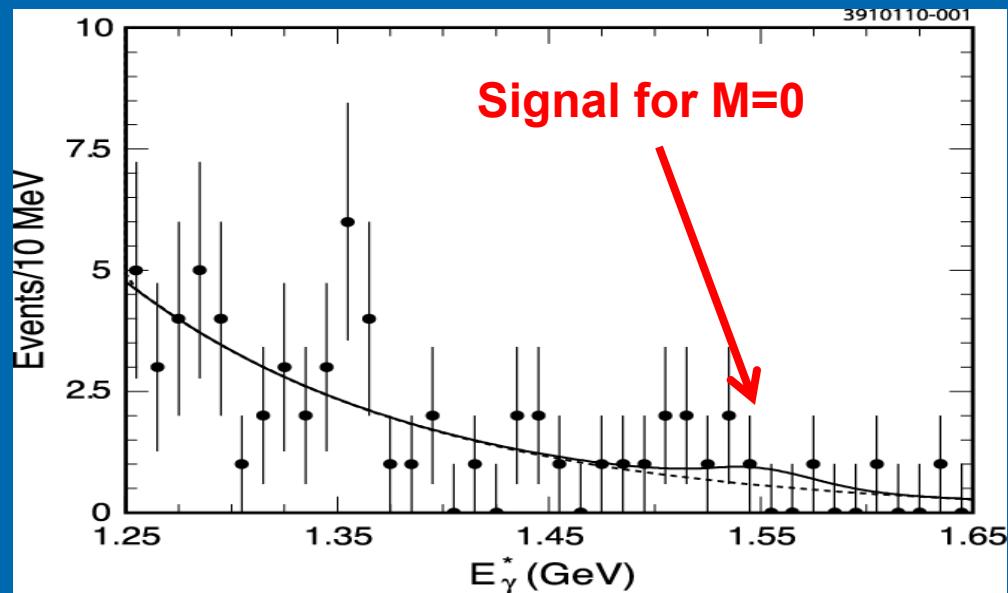
No peak, smooth bqd, but what is it?

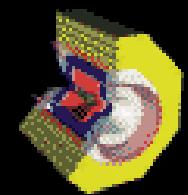
- MC says: anti-neutrons from  $J/\psi \rightarrow n\bar{n}$  ! ( $B=0.22\%$ )
- Imperfect anti-neutron shower shape modeling in GEANT3



# Results for $J/\psi \rightarrow \gamma + \text{invis}$

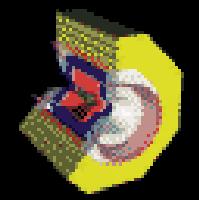
- Fit signal + smooth bgd
- Scan  $M(\text{invisible})$
- Systematics < Statistics
- $B(J/\psi \rightarrow \gamma + \text{invis})$   
 $< 3-6 \times 10^{-6}$  for  $M < 1 \text{ GeV}$
- $\cos^2\theta / \tan^2\beta \leq 0.084$
- Could directly limit Higgs mixing angle  $\theta$  (no  $\tan\beta$  dependence) by combining with a similar limit from  $\Upsilon \rightarrow \gamma + \text{invis}$





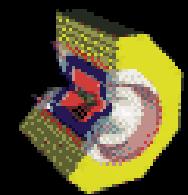
# Conclusions

- Radiative decays of charmonium continue to illuminate many physics topics
- CLEO has improved branching fractions for  $J/\psi$ ,  $\psi(2S)$ ,  $\psi(3770) \rightarrow \gamma + \pi^0 / \eta / \eta'$ 
  - $B(\psi(2S) \rightarrow \gamma \eta') / B(\psi(2S) \rightarrow \gamma \eta) > 59.$ 
    - This ratio is ~5 for  $J/\psi \rightarrow \gamma \eta'$ . Why the discrepancy??
  - Improved  $\eta'$  decay BR's (see backup slides)
- $R_\gamma \equiv B(\gamma gg) / B(ggg) = 0.097 \pm 0.026 \pm 0.016$  for  $\psi(2S)$ 
  - $0.137 \pm 0.017$  for  $J/\psi$  . Differ by  $\sim 1.1\sigma$
  - $0.03$  for  $\Upsilon(1S/2S/3S)$
- $B(J/\psi \rightarrow \gamma + \text{invis}) \sim 3-6 \times 10^{-6} \cos^2 \theta / \tan^2 \beta \leq 0.084$ 
  - Improved  $\eta' \rightarrow \text{invisible}$  limit (see backup slides)



# Backup

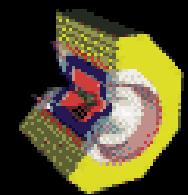




# $\eta'$ Branching Fractions

- Our rare  $\eta'$  decays paper pins down the branching fractions beyond the top 5 to be 0.8%
- Hence the top 5 must add up to 99.2%
- Use  $J/\psi \rightarrow \gamma \eta'$  events
- Impose above constraint & account for error correlations
- BRs **consistent** with PDG fit (which has \*many\* inputs)
  - Comparable precision from a single experiment!
  - Most precise single measurement of ALL 5 modes

Mode	This result	PDG [9]	# $\sigma$
$\eta' \rightarrow \pi^+ \pi^- \eta$	$42.4 \pm 1.1 \pm 0.4$ (2.6%)	$44.6 \pm 1.4$ (3.1%)	-1.2
$\eta' \rightarrow \pi^0 \pi^0 \eta$	$23.5 \pm 1.3 \pm 0.4$ (5.9%)	$20.7 \pm 1.2$ (5.8%)	1.5
$\eta' \rightarrow \pi^+ \pi^- \gamma$	$28.7 \pm 0.7 \pm 0.4$ (2.8%)	$29.4 \pm 0.9$ (3.1%)	-0.6
$\eta' \rightarrow \omega \gamma$	$2.34 \pm 0.30 \pm 0.04$ (13%)	$3.02 \pm 0.31$ (10%)	-1.6
$\eta' \rightarrow \gamma \gamma$	$2.25 \pm 0.16 \pm 0.03$ (7.4%)	$2.10 \pm 0.12$ (5.7%)	0.7



# Rare $\eta'$ decays via $J/\psi \rightarrow \gamma\eta'$

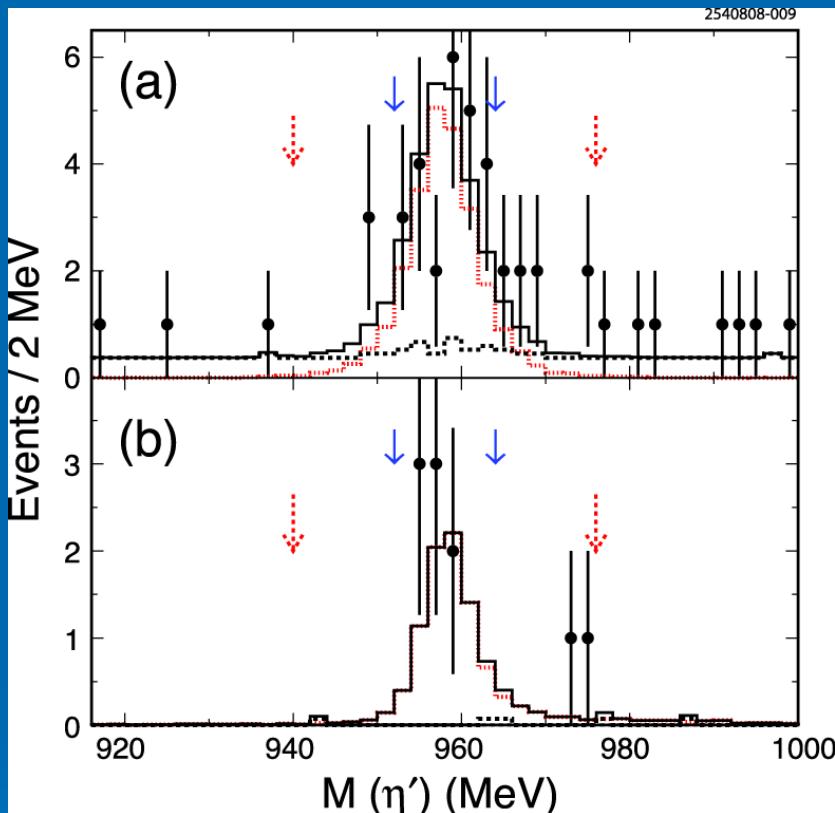
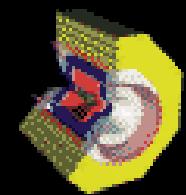
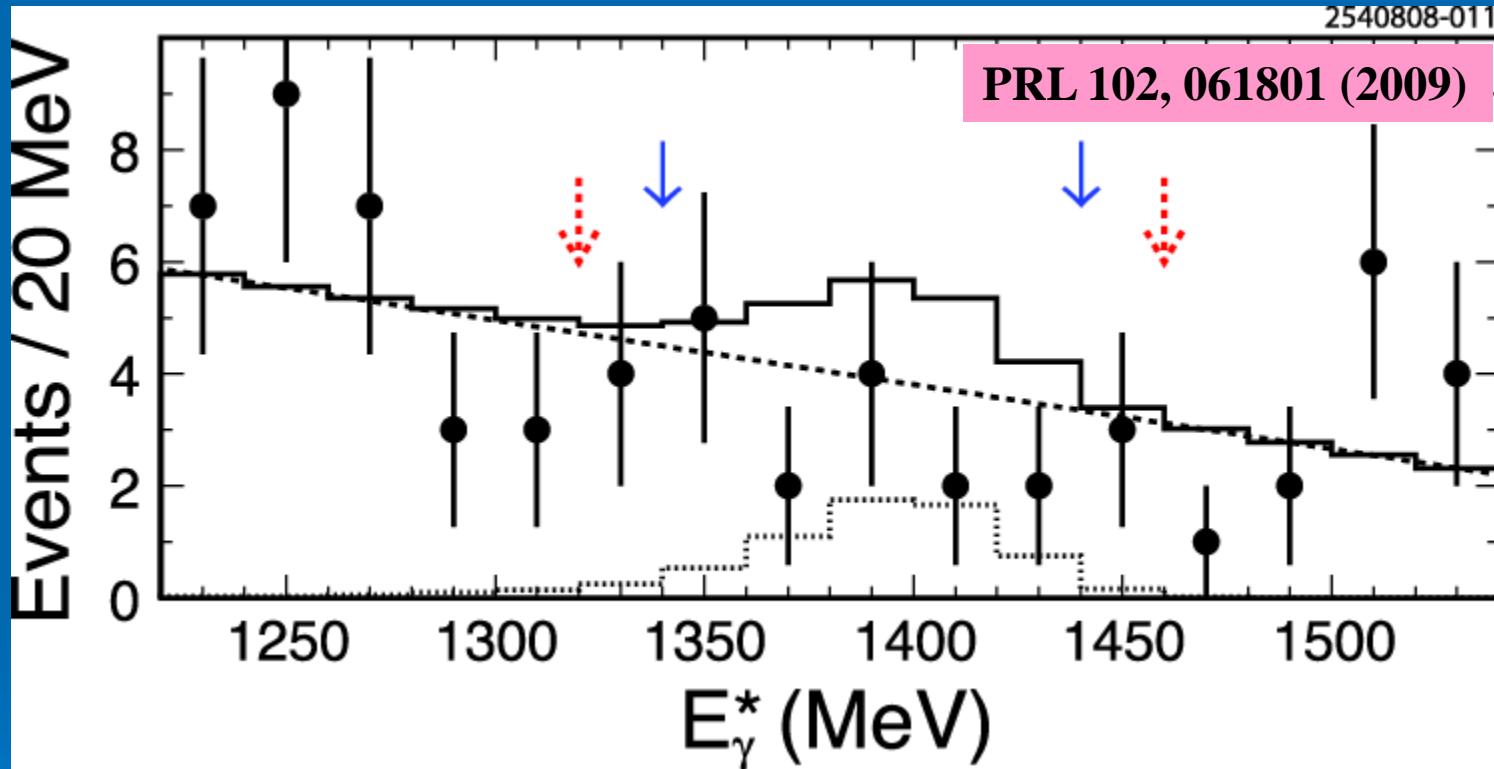


TABLE I. Results for  $\eta' \rightarrow X$  search, showing for each mode  $X$  the efficiency relative to that of the normalization mode  $\eta' \rightarrow \pi^+ \pi^- \eta[\gamma\gamma]$ ,  $\epsilon/\epsilon_0$ ; the net number of signal events, after background subtractions,  $N$  (or 90% C.L. upper limit where indicated with “<”); the branching fraction ratio  $R$  [see text]; the absolute branching fraction  $B \equiv \mathcal{B}(\eta' \rightarrow X)$  and its previous upper limit  $P$  [7]. Entries for  $R$  and  $B$  include systematic errors.

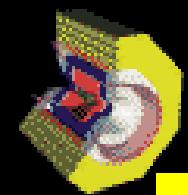
Mode $X$	$\epsilon/\epsilon_0$	$N$	$R(10^{-3})$	$B(10^{-4})$	$P(10^{-4})$
$\pi^+ \pi^- \eta[\gamma\gamma]$	1.00	$1756 \pm 42$	...	...	...
$\pi^+ \pi^- \pi^0$	0.55	$20.2^{+6.1}_{-4.8}$	$21^{+6}_{-5} \pm 2$	$37^{+11}_{-9} \pm 4$	<500
$\pi^+ \pi^- e^+ e^-$	0.31	$7.9^{+3.9}_{-2.7}$	$14^{+7}_{-5} \pm 3$	$25^{+12}_{-9} \pm 5$	<60
$\pi^+ \pi^- \mu^+ \mu^-$	2.14	<4.8	<1.3	<2.4	...
$2(\pi^+ \pi^-)$	1.02	<2.3	<1.4	<2.4	<100
$\pi^+ \pi^- 2\pi^0$	0.18	<4.1	<15	<27	...
$2(\pi^+ \pi^-)\pi^0$	0.21	<3.6	<11	<20	<100
$3(\pi^+ \pi^-)$	0.47	<2.3	<3.0	<5.3	<100
Invisible	0.74	<5.8	<5.4	<9.5	<14



# $\eta' \rightarrow \text{Invisible}$ via $J/\psi \rightarrow \gamma\eta'$

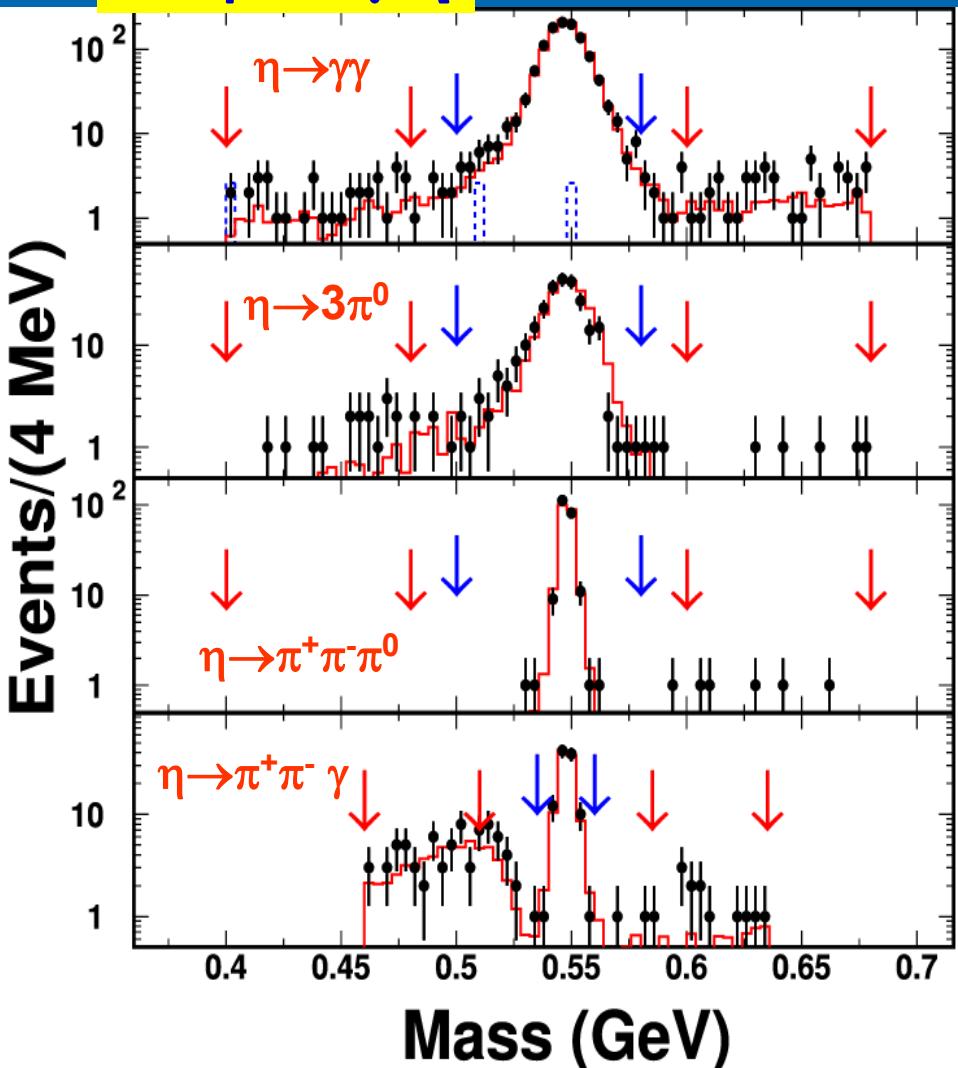


- CLEO:  $B(\eta' \rightarrow \text{invisible}) < 9.5 \times 10^{-4}$

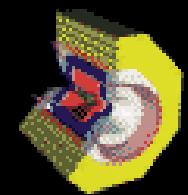


# Background & Cross-feed

$J/\psi \rightarrow \gamma\eta$



- Use mass sidebands
- Cross-feed: from other  $\eta(')$  decays
  - Included in MC histogram in red
- 1<sup>st</sup> subtract cross-feed in signal & sidebands
- Assume remaining bgd is linear in mass
- Small for most modes
- Also look in  $\pi^+\pi^-$  recoil mass sidebands
  - Even smaller bgd there



# Mass Windows; $E_\gamma$ cut

Mode	Window	Lower SB	Upper SB	SB Factor
$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi, \pi^+ \pi^-$ -recoil	3087-3107	2980-3080	3114-3214	10
$\pi^0 \rightarrow \gamma\gamma$	110-160	50-100	170-220	2
$\eta \rightarrow \pi^+ \pi^- \gamma, e^+ e^- \gamma$	535-560	460-510	585-635	4
$\eta \rightarrow$ others	500-580	400-480	600-680	<b>2</b>
$\eta' \rightarrow \gamma\gamma, \pi^0 \pi^0 \eta(\gamma\gamma)$	920-995	730-880	1035-1185	4
$\eta' \rightarrow$ others	945-970	890-940	975-1025	4
$\omega \rightarrow \pi^+ \pi^- \pi^0$	750-814	-	-	-

The default photon energy cut is 37 MeV (~2% of beam energy).  
The modes below have more a restrictive cut to suppress bkgd.

Mode	Photon energy cut (MeV)
$J/\psi \rightarrow \gamma\eta', \psi(2S) \rightarrow \gamma\eta', \eta' \rightarrow \pi^+ \pi^- \gamma$	100
$J/\psi \rightarrow \gamma\eta', \psi(2S) \rightarrow \gamma\eta', \eta' \rightarrow \pi^+ \pi^- \eta, \eta \rightarrow \pi^+ \pi^- \gamma$	100
$J/\psi \rightarrow \gamma\eta, \psi(2S) \rightarrow \gamma\eta, \eta \rightarrow \pi^+ \pi^- \gamma$	100
$\psi(2S) \rightarrow \gamma\pi^0, \pi^0 \rightarrow \gamma\gamma$	300